TOWARDS AN ALL-OPTICAL ACCESS TO THE LOWEST NUCLEAR EXCITATION IN ^{229m}Th*

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The isomeric first excited state of ^{229}Th exhibits the lowest nuclear excitation energy in the whole landscape of known nuclei. Due to its extremely low energy of 7.6(5) eV and its long lifetime of *ca.* 10^4 s, it exhibits an extremely sharp relative linewidth of $\Delta E/E \approx 10^{-20}$, thus rendering ^{229m}Th an ideal candidate for a nuclear optical clock with very high accuracy. An experimental approach is introduced, based on a spatially decoupled population and de-excitation of the isomeric state, aiming at a first direct identification of the 163(11) nm UV fluorescence and targeting to improve on the accuracy of the transition wavelength, thus enabling an all-optical control via laser excitation.

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1. Introduction

The isomeric first excited state of the isotope ^{229}Th exhibits the lowest nuclear excitation energy of all known atomic nuclei, indirectly measured as 7.6(5) eV [1] and corresponding to a transition wavelength of 163(11) nm. The expected isomeric lifetime is $\tau = 3$–5 hours, leading to an extremely sharp relative linewidth of $\Delta E/E \approx 10^{-20}$, 5–6 orders of magnitude smaller than typical atomic relative linewidths. For an adequately chosen electronic state, the frequency of the nuclear ground-state transition will be independent from influences of external fields, thus rendering ^{229m}Th an ideal candidate for an ultra-stable nuclear optical clock [2]. Moreover, speculations

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about a potentially drastically enhanced sensitivity of the ground-state transition of ^{229m}Th for eventual time-dependent variations of fundamental constants (*e.g.* fine structure constant α) have been reported [3].

2. Experimental approach

Our experimental approach towards an identification of the UV fluorescence in ^{229m}Th is based on a spatial decoupling of population and deexcitation of the low-lying isomer. While presently its direct laser excitation fails due to the extremely narrow transition line width and the limited knowledge of the transition energy, instead a 2% α-decay branch from ^{233}U to ^{229m}Th can be used to populate the isomer. Thus we place a ^{233}U source inside the Garching buffer-gas stopping cell [4], such that the ^{229m}Th α recoil nuclei will be stopped in 40 mbar helium and will be guided by RF and DC fields to a nozzle exit, where they are dragged by the gas flow into the vacuum regime of a subsequent extraction radiofreqency quadrupole (RFQ). This arrangement allows to prevent all prompt background processes like conversion or prompt excitations from detection. Besides ^{229}Th and potentially sputtered ^{233}U nuclei, also other α recoil nuclei can be extracted from the gas cell, therefore an efficient quadrupole mass separator (mass resolution about 1 u) was added behind the extraction RFQ, based on a design by the Giessen group for SHIPTRAP at GSI [5]. An ion collection system was designed behind the QMS to achieve an optimized efficiency and to realize a small collection surface in order to provide an almost point-like UV emission source. This will be achieved by a nozzle-like focusing electrode and a micro-electrode collection surface (held at a potential of -500 V) with 50 μm diameter. Subsequently, the isomeric UV fluorescence has to be focused efficiently onto the detection stage. Simulations using an optical ray-tracing code were performed to benchmark different options for the UV optical system. Optimization criteria were a maximized photon collection efficiency and a small image magnification, aiming at an optimized signal contrast. Spherical aberrations limit the performance of lens-based setups, leading to consider setups based on parabolic mirrors, which are favourable compared to aspheric lenses due to their larger acceptance and broader wavelength dynamics. Arrangements to focus the UV radiation that have been comparatively studied are (A) two spherical lenses, (B) a parabolic mirror and a (spherical) convex lens, (C) a parabolic mirror and an aspherical lens and (D) 2 parabolic mirrors (shown in Fig. 1). Our favoured solution is scenario D in Fig. 1, where the collection surface is positioned in the focus of an annular parabolic mirror (dielectric coated aluminium mirror), which parallelizes the UV light and transmits it onto a second parabolic mirror. This mirror is shaped via a central hole such that its retracted focal point lies

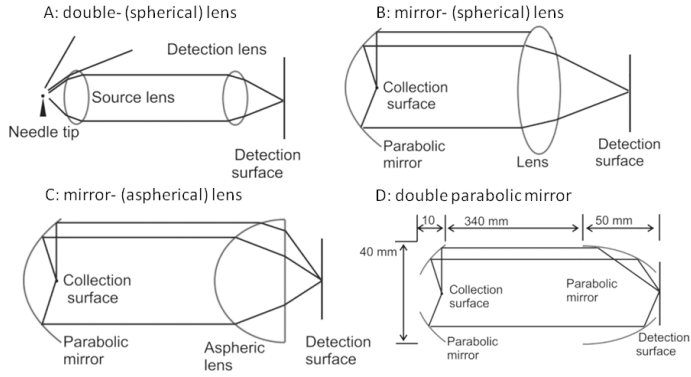

Fig. 1. Schematical drawings of the four UV optical arrangements studied to focus the ^{229m}Th UV fluorescence onto an MCP detector.

in the plane of the subsequent MCP detector, where electrons are generated and accelerated onto a phosphor screen, which is observed by a CCD camera. Inbetween the two mirrors various filters with sharp absorption edges ($\leq$ 1 nm) will be used to accurately determine the transition wavelength. This arrangement will be sensitive to detect the ^{229m}Th decay in a wavelength region of about 130–190 nm. With an optical efficiency of 35.8% and typical reflectivities of 70% for each of the two mirrors, a total UV photon collection efficiency of 17.5% can be achieved. This arrangement allows for a small image size of *ca.* 70 μm diameter. Thus, a very high signal contrast (see Table I) compared to the MCP dark count rate can be achieved. Presently, we are operating a ^{233}U source with an effective Th activity of 5.0 kBq, while we are already licensed to increase this by a factor of 16. Together with the 2% α-decay branch to the first excited state, presently 100 (future: 1600) ^{229m}Th ions per second enter the buffer gas stopping volume. Figure 2 shows a schematical view of the complete experimental setup. We expect an extraction efficiency from the gas cell for ^{229m}Th^{2+} of 7%, the QMS transport

TABLE I

Properties of four optical scenarios to focus the ^{229m}Th UV fluorescence.

	A	B	C [160 nm]	D
Photon collect. efficiency [%]	0.72	19.0	19.4	17.5
Counting rate [s^{-1}]	0.0026	0.068	0.069	0.063
Image spotsize [mm]	0.17	0.51	0.067	0.066
Effective image magnification	3.5	10.2	1.33	1.33
Image intensity [s^{-1}mm^{-2}]	0.11	0.34	19.9	18.1
Signal contrast	2.2	6.8	398	362

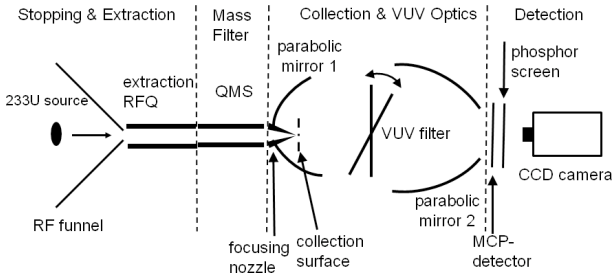

Fig. 2. Experimental scheme for the identification of UV fluorescence from the de-excitation of the isomeric first excited state of ^{229m}Th.

efficiency will amount to about 80%. An ion collection efficiency of 40% is expected. 17.5% of the 7.6 eV photons will be focused by the double-mirror arrangement onto the UV-sensitive MCP, with a typical detection efficiency of 16%. Finally, this leads to total efficiency of 1.2×10^{-5}, corresponding to a detectable UV photon rate of 0.06/s at present, which can be increased to 0.96/s for a future 80 kBq source. Even the present source strength will allow for a signal/background-ratio of 362:1, which could be increased further to *ca.* 5800:1. Already the present superb signal contrast is expected to be sufficient to detect the ^{229m}Th de-excitation even if non-radiative losses via bridge processes or conversion decays in the range of 90% would occur.

Thus, we present here an experimental concept that has been studied and designed quantitatively in all components, either via preparatory experimental work or by simulations, ending in a scenario with high enough sensitivity and UV photon yield to achieve a first direct identification of the 7.6 eV fluorescence from the ^{229m}Th ground-state decay with an improved energy accuracy, laying the foundation for a subsequent laser development targeting an all-optical control of this intriguing nuclear transition that builds a bridge between atomic and nuclear physics and bears intriguing perspectives both in metrology (nuclear clock) as in fundamental physics (α(t)).

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